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ORIGINAL PAPER

Soil remediation of degraded coastal saline wetlands by irrigation with paper mill effluent and plowing

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Abstract: Combined with anti-waterlogging ditches, irrigation with treated paper mill effluent (TPME) and plowing were applied in this study to investigate the effects of remediation of degraded coastal saline-alkaline wetlands. Three treatments were employed, viz., control (CK), irrigated with 10 cm depth of TPME (I), and plowing to 20 cm deep before irrigating 10 cm depth of TPME (IP). Results show that both I-treatment and IP-treatment could improve soil structure by decreasing bulk density by 5% and 8%. Irrigation with TPME containing low salinity stimulated salts leaching instead of accumulating. With anti-waterlogging ditches, salts were drained out of soil. Irrigation with 10 cm depth of TPME lowered total soluble salts in soil and sodium adsorption ration by 33% and 8%, respectively, but there was no significant difference compared with CK, indicating that this irrigation rate was not heavy enough to remarkably reduce soil salinity and sodicity. Thus, irrigation rate should be enhanced in order to reach better effects of desalinization and desodication. Irrigation with TPME significantly increased soil organic matter, alkali-hydrolyzable nitrogen and available phosphorus due to the abundant organic matter in TPME. Plowing increased soil air circulation, so as to enhance mineralization of organic matter and lead to the loss of organic matter; however, plowing significantly improved soil alkali-hydrolyzable nitrogen and available phosphorus. Improvements of physicochemical properties in I-treatment and IP-treatment both boosted soil microbial population and activity. Microbial biomass carbon increased significantly by 327% (I-treatment) and 451% (IP-treatment), while soil respiration increased significantly by 316% (I-treatment) and 386% (IP-treatment). Urease and dehydrogenase activities in both I-treatment and IP-treatment were significantly higher than that in CK. Phosphatase in IP-treatment was significantly higher than that in CK. Compared to I-treatment, IP-treatment improved all of the soil properties except for soil organic matter. The key to remediation of degraded saline-alkaline wetlands is to decrease soil salinity and sodicity; thus, irrigation plus plowing could be an ideal method of soil remediation.

Keywords: anti-waterlogging ditches; degraded saline-alkaline wetlands; plowing; remediation; soil property; treated paper mill effluent

Introduction

Large area of reed wetlands located in the inland of Yellow River Delta play significant roles in environmental protection. However, the increase in groundwater salinity and water level caused by seawater erosion and inappropriate use of agricultural water led to secondary soil salinization under the climate of higher evaporation than rainfall, and then resulted in the degradation of reed wetlands. Consequently, ecological security was confronted with great challenge. Thus, it is urgent to remedy degraded saline-alkaline wetlands and rebuild ecological protection for the ecological security of Yellow River Delta in order to stimulate the development of ecological economy.

The key to remediation of saline-alkaline wetlands is to reduce soil salinity and sodicity, because soil salinity and sodicity are the two main inhibitory factors for plants growth. In addition, saline-alkaline soil is usually poor in nutrients (Lakhdar et al. 2008); thus, another emphasis is to improve soil nutrients. Leaching soil salts by irrigation becomes a main way for desalinization. It was reported that irrigation with introduced water in Yellow River Delta could lighten soil salinity and sodicity, but could not be popularized due to large project and expenses (Wu

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2003). Many studies (Kannan and Oblisami 1990a; Kumar et al. 2010; Roy and Prasad 2008; Yan and Pan 2010) demonstrated that irrigation with paper mill effluent could enhance soil nutrients level and microbial activity remarkably; whereas, irrigation water with high salinity or inappropriate way of irrigation could bring in soil salts accumulation and intensify soil salinization. Thus, drainage system should be built when irrigating with wastewater. A paper mill, which discharges 26,000 $m^3 \cdot d^{-1}$ effluents, is located near the degraded saline-alkaline wetlands in Zhanhua County, Yellow River Delta. The effluent quality was obviously improved after treated through biological pond treatment system. Using the treated paper mill effluent as irrigation water could not only solve shortage of irrigation water, but also reduce effluent discharge. However, degraded saline-alkaline wetlands were compacted in soil, which restrains the effect of leaching through irrigation. Plowing was reported to be capable of loosening soil and strengthening permeability (Moreno et al. 1997; Olaoye 2002); thus, plowing before irrigation could stimulate soil leaching. In this study, we investigated the improvements of soil properties to reflect the effectiveness of remediation by irrigation with treated paper mill effluent and plowing on degraded saline-alkaline wetlands.

Table 1. Soil properties of experimental region

Parameters	Value
pH	7.89±0.03
Bulk density ($g \cdot cm^{-3}$)	1.60±0.01
Total soluble salt (%)	2.32±0.06
Sodium adsorption ration (SAR)	17.09±0.45
Organic matter ($g \cdot kg^{-1}$)	8.41±0.12
Alkali-hydrolyzable N ($mg \cdot kg^{-1}$)	13.16±0.30
Available P ($mg \cdot kg^{-1}$)	8.29±0.25
Available K ($mg \cdot kg^{-1}$)	287.9±3.0
Total N ($g \cdot kg^{-1}$)	0.55±0.16
Total P ($g \cdot kg^{-1}$)	0.63±0.03
Total K ($g \cdot kg^{-1}$)	21.15±4.35
Microbial biomass C ($mg \cdot kg^{-1}$)	30.18±0.30
Soil respiration (mg CO_2 $kg^{-1} \cdot d^{-1}$)	168.8±4.7
qCO_2 (d^{-1})	1.53±0.04
Urease activity (mg NH_3-N $g^{-1} \cdot d^{-1}$)	0.06±0.01
Phosphatase activity (mg PNP $g^{-1} \cdot d^{-1}$)	0.11±0.01
Dehydrogenase activity (μg TPF g^{-1} $20h^{-1}$)	2.39±0.06

Note: average ±standard deviation (n=9)

Materials and methods

Study site description

This study was conducted on the degraded coastal saline-alkaline wetlands (37°46′37.6″ N, 118°07′37.9″ E) in Zhanhua County, Yellow River Delta, China. The climate of study region is known as continental monsoon climate, with annual temperature of 12.5°C, annual average rainfall of 600 mm, and annual evaporation of 1,800–2,000 mm. Soil of the degraded wetlands in the study area was in different levels of salinization. We chose severely degraded saline-alkaline wetlands that were not covered with any plants as study area. The soil belongs to coastal calcareous soil with abundant of salts accumulated in the surface. The main characteristics were shown in Table 1.

Experimental design

The irrigation water used in this study was treated paper mill effluent (TPME) that derived from a paper mill near to the study region. The paper mill effluent was treated in a system consisted of sedimentation tank, anaerobic pond, aerobic pond and facultative pond. Chemical characteristics of the raw and treated paper mill effluents were shown in Talbe 2. We set three 100-m^2 experimental plots. One plot was treated with irrigation of TPME at 10 cm depth without plowing (named as I-plot), the other plot was treated with irrigation of TPME at 10 cm depth with plowing to 20 cm deep (named as IP-plot), and the remained one was blank (CK) without any treatment. Geotextile was buried to 30 cm deep between plots to avoid interaction. Anti-waterlogging ditches were also built around plots for drainage. Irrigation frequency was dependent on evaporation and leaching speed, and it was conducted after field drying for one week. There was no irrigation during winter (from December 2007 to March 2008).

Table 2. Chemical characteristics of raw and treated paper mill effluent

	pH	COD ($mg \cdot L^{-1}$)	BOD_5 ($mg \cdot L^{-1}$)	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)	Salinity ($mg \cdot L^{-1}$)	Na^+ (%)
Raw effluent	8.50	2500	750	60.47	9.56	2750	0.15
Treated effluent	7.44	520	84	28.43	7.22	2080	0.12

Soil sampling and analysis

Five samples were taken with soil corers in an "S" path in each plot before experiment in May 2007 and after experiment in March 2008. A part of the fresh soil samples was stored at 4ºC for microbial analysis, and the remaining was dried, ground, screened through a 2-mm sieve and stored in sealed polyethylene bags at 4ºC until analysis.

The parameters of paper mill effluent and soil physicochemical properties were analyzed according to the standard methods (National Environmental Protection Agency, 2002; Ba 2005). Thereinto, alkali-hydrolyzable nitrogen was analyzed by Alkali-hydro diffusion method using 1 M NaOH as alkalizer; available phosphorus was determined by using 0.5 M bicarbonate extraction with a spectrophotometer, and available potassium was analyzed by using 1 M ammonium acetate extraction with a flame photometer. Microbial biomass carbon (MBC) was determined by the chloroform- fumigation-extraction method and soil

respiration (SR) was determined by NaOH adsorption methods (Wichem et al. 2006). Soil urease, phosphatase and dehydrogenase activities were analyzed by sodium phenoxide colorimetric method, disodium phenyl phosphate colorimetric method and TTC methods (Guan 1986). Soil sodium adsorption ration (SAR) was calculated according to the Equation 1:

$$\mathrm{SAR}=\frac{[\mathrm{Na}^{+}]}{\sqrt{0.5([\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}])}} \quad (1)$$

where Na^{+}, Ca^{2+} and Mg^{2+} are in mmol·L^{-1}, respectively.

Soil metabolic quotient (qCO_2) was calculated with MBC and SR according to the Equation 2:

$$\mathrm{qCO_2}=\frac{\mathrm{SR}}{\mathrm{MBC}} \quad (2)$$

where SR and MBC are in mg CO_2-C ·kg^{-1}·d^{-1} and mg·kg^{-1}.

Statistical analysis

The effects of different treatments on soil properties were tested by a one-way analysis of variance and comparisons among means using least significant difference test at $p<0.05$ (Townend 2003). Correlation analysis was also made between soil properties. All of the statistical procedures were carried out with SPSS software.

Results and discussion

Soil bulk density (SBD)

SBD, an important indicator that represents soil structure, influences soil fertility directly. Soil of the degraded saline-alkaline wetlands in this study was compacted and viscous, with average bulk density of 1.60 g·cm^{-3} (Table 1). At the end of the experiment, SBD in CK plot had a little decrease but had no significant difference. SBD in I-treatement and IP-treatment plots were both lower than that in CK plot; furthermore, SBD in IP-treatment was significantly lower than that in I-treatment plot (Fig. 1), indicating that irrigation with TPME and plowing could decrease SBD. SBD in I-treatment and IP-treatment was decreased by 5% and 8%, respectivly. Irrigation with paper mill effluent, which is abundant in organic matte such as lignin, could improve soil structure by the more soil aggregate formed by trapping the organic matter in soil. Khaleel et al. (1981) also reported that increase of organic matter was beneficial to the decrease of SBD. Plowing could lower SBD by destroying viscous structure in the surface layer of soil. This finding was agreed with the study conducted by Barzagar et al (2003). Zhang et al. (2003) also reported that plowing could decrease SBD and it was more evident in soil layer of 0–20 cm.

Soil salinity and sodicity

Soil of the degraded wetlands had high salinity and sodicity with white alkaline spots scattered on the surface. Total soluble salts and SAR of the original soil reached 2% and 17%, respectively (Table 1).

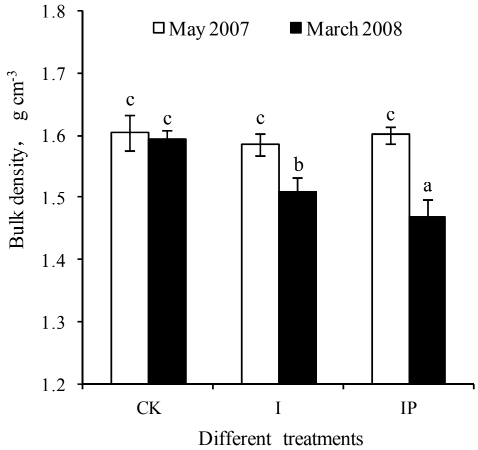

Fig. 1 Influence of irrigation with treated paper mill effluent and plowing on soil bulk density. Different letters represent a significant difference ($p<0.05$).

Total soluble salts (TSS) of soil are highly impacted by rainfall and temperature. Rainfall could leach soil salts, while the increase of temperature could promote evaporation and consequently result in accumulation of salts in soil surface. Under the influence of rainfall, temperature variation, and the anti-waterlogging ditches, soil TSS in CK plot was reduced by 27% in the next March (2008) (Fig. 2a). TSS in I-treatment decreased by 34%, which had no significant difference compared to CK (Fig. 2a). This result indicated that irrigation with 10 cm depth of TMPE without plowing is not enough to lighten soil salts significantly. Many studies (Kannan and Oblisami, 1990a; Kumar et al. 2010; Roy and Prasad, 2008) presented salts accumulation on soil surface after irrigation with paper mill effluent. However, in the present study, soil salts decreased instead of accumulating. On one hand, it was attributed to the low salinity (only 2,080 mg·L^{-1}) of TPME used, which could help leaching soil salts; on the other hand, there were anti-waterlogging ditches around the plots, which could drain salts out of soil system. IP treatment reduced soil TSS by 39%, which was significantly lower than the decrease of CK (Fig. 2a), demonstrating that the joint action of irrigation with TPME at 10 cm depth and plowing could significantly reduce soil salts. Plowing can improve soil structure and permeability, so as to help salts leaching. Sadiq et al. (2007) also reported the reduction of soil salts resulting from plowing. Hafele et al. (1999) compared dry plowing and wet plowing (plowing under soil water saturated condition) and found that wet plowing was more effective in decreasing soil salts. This is because more soluble salts were brought to soil by wet plowing and then leached out. IP treatment in this study was similar to wet plowing.

SAR is an important indicator of soil sodicity. SAR in CK plot

did not change significantly before and after experiment (Fig. 2b), while SAR in I-treatment and IP-treatment decreased by 8% and 16%, respectively. There was significant difference in SAR between IP-treatment and CK, but no significant difference was found between I-treatment and CK. This result demonstrated that irrigation with TPME at 10 cm depth could not significantly reduce soil SAR, while joint action of irrigation and plowing could. This was the same as soil salinity. Irrigation and plowing lessen soil sodicity by the following mechanisms: (1) irrigation with TPME and plowing both could promote the decrease of soil Na^+; (2) since the soil in this study area is calcareous saline-alkaline soil that is rich in $CaCO_3$, irrigation and plowing could increase pressure of CO_2 in soil dissolve $CaCO_3$ to produce Ca^{2+}, and consequently promote exchange adsorption of Na^+-Ca^{2+}. This result was in agreement with the studies conducted by Sadiq et al. (2007) and hafele et al. (1999).

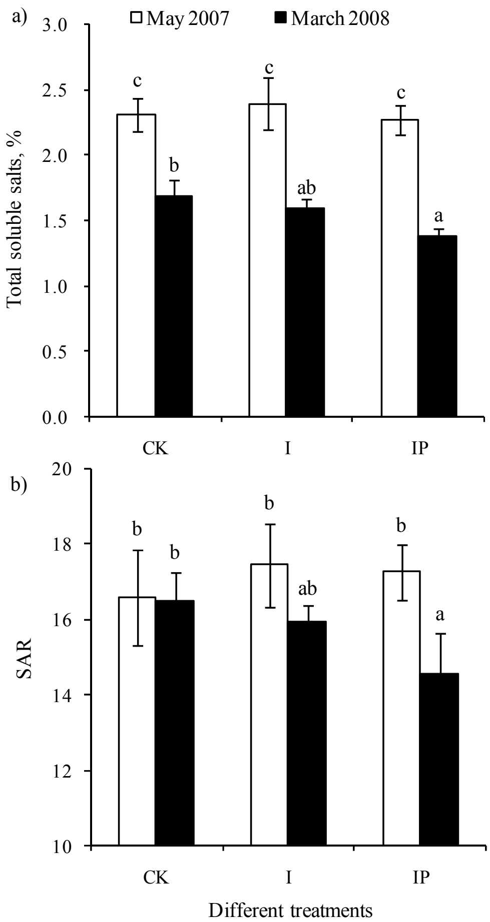

Fig. 2 Influence of irrgation with treated paper mill effluent and plowing on soil salinity (a) and sodicity (b). Different letters represent a significant difference (p <0.05).

Soil nutrients

All the soil nutrients except potassium were originally low. Soil organic matter (SOM), alkali-hydrolyzable nitrogen (AN), available phosphate (AP) and available potassium (AK) were 8.41 $g \cdot kg^{-1}$, 13.16 $mg \cdot kg^{-1}$, 8.29 $mg \cdot kg^{-1}$, and 288 $mg \cdot kg^{-1}$ originally, respectively (Table 1). In the next March (2008), SOM in CK plot, I-treatment and IP-treatment increased by 66%, 77% and 72%, respectively (Table 3). Significant difference of SOM in CK was attributed to that rainfall and anti-waterlogging ditches led to the huge reduction of soil salts, which stimulated the growth of a few reeds in the originally bare filed. It could be deduced that the reduction of soil salts was the key to remediation of degraded saline-alkaline wetlands. SOM increase in I-treatment and IP-treatment plots were higher than that in CK plot, indicating that abundant of organic matter, such as plant fiber and lignin in TPME were adsorbed in soil, and then elevated SOM. At the end of the experiment, SOM in I-treatment and IP-treatment were higher than that in CK, but did not reach significant level. This demonstrates that irrigation with 10 cm depth of TMPE each time was not strong enough for increasing SOM. Thus, as far as SOM is concerned, irrigation rate should be increased. Plowing is beneficial to enhancement of soil permeability, but fast permeation would result in the loss of organic matter. This can explain why SOM in IP-treatment was lower than that in I-treatment. Our reslut is in accordance with the studies conducted by Lal (1997) and Sun et al. (2010). The difference in SOM between I and IP treatments was not significant, indicating that plowing would not lead to abundant loss of SOM.

Table 3 Influence of irrigation with treated paper mill effluent and plowing on soil nutrients

Time	Treat-ment	SOM ($g \cdot kg^{-1}$)	AN ($mg \cdot kg^{-1}$)	AP ($mg \cdot kg^{-1}$)	AK ($mg \cdot kg^{-1}$)
May-2007	CK	8.55±0.47a	13.11±0.28a	8.02±0.35b	287±12a
	I	8.31±0.19a	13.48±0.52a	8.50±0.17b	291±13a
	IP	8.37±0.23a	12.89±0.13a	8.36±0.17bc	285±17a
March-2008	CK	14.19±0.36b	22.67±0.71b	7.28±0.28a	349±13b
	I	14.70±0.75b	38.21±0.66c	8.87±0.35c	339±14b
	IP	14.39±0.52b	41.37±0.68d	8.99±0.34c	358±17b

Note: average ±stamdard deviation (n=3). Different letters in the same row indicate significant difference (p<0.05). SOM---Soil organic matter; AN---Alkali-hydrolyzable nitrogen; AP---Available phosphate; AK---Available potassium. I-treatment means irrigation with rate of 10 cm TPME without plowing; IP-treatment means irrigation with rate of 10 cm TPEM with plowing.

At the end of the experiment, AN in all the plots increased significantly (by 73% (CK), 184% (I), and 221% (IP), respectively. Obviously AN in I-treatment and IP-treatment plots were both significantly higher than that in CK, indicating irrigation with TPME and plowing could both improve soil AN. On one hand, the enhancement of AN could be attributed to the stronger mineralization caused by improvement of SOM; on the other hand, it could be due to the high N in TPME (Table 2). AN in IP-treatment plot was higher than that in I-treatment plot, indicating that plowing could increase soil AN as long as soil is not short of organic N. This is because plowing could improve soil permeability, increase quantity of O_2, and consequently stimulated the mineralization of organic N.

In contrary to AN, soil AP in CK plot significantly decreased compared to the beginning. This is caused by the lower miner-

alization of organic P in winter. Nevertheless, AP in I-treatment and IP-treatment plot increased and both were significantly higher than CK, indicating that irrigation with TPME and plowing could improve soil AP. On one hand, it should be attributed to the high P in TPME (Table 2); on the other hand, higher SOM mineralization improved AP, and furhermore, plowing also simulate mineralization of soil organic P.

In March 2008, there was no significant difference in AK between I-treatment plot and CK plot, so well as between IP-treatment and CK, indicating that irrigation with TPME and plowing neither improved soil AK. This should be attributed to the high original amount of AK in the studied field, and irrigation as well as plowing did not show significant effect. However, AK in all the plots increased significantly, compared to that at beginning of the experiment. AK increase in all plots was caused by the freeze-thaw effect, as freeze-thaw cycles could increase availability of potassium (Sjuren et al. 2005).

Soil microbial properties

Microbial biomass carbon (MBC) is an important indicator of soil microbial population. Compared to the original value, MBC in CK, I-treatment and IP-treatment plots increased by 222%, 327% and 451%, respectively (Table 4). The increases of MBC in CK plot should be attributed to: (1) the reduction of soil salts, which alleviated the stress to microbes; (2) the metabolizing materials introduced by plant residues stimulated microbial proliferation. There was significant difference in MBC among the three plots. The enhancement of MBC should be attributed to plowing that lead to more aeration and to irrigation with TPME. Irrigation with TPME improved soil MBC mainly through three ways. Firstly, irrigation introduced plenty of metabolizing materials; secondly, it ameliorated soil structure, which created more suitable environment for microbial proliferation; thirdly, it could alleviate drastic change of temperature by keeping soil moisturious, and then reduce the negative impact on microbes. Kannan and Oblisami (1990a) and Sebastian et al. (2009) also reported that irrigation with paper mill effluent could improve soil microbial population. Plowing may lead to the increase of soil evaporation; however it can also improve soil structure, enhance soil permeability, and reduce soil salinity and sodocity. Under the multiply influences, plowing could increase soil MBC.

Table. 4 Influence of irrigation with treated paper mill effluent and plowing on soil microbial properties

Time	Treatment	MBC ($mg\cdot kg^{-1}$)	SR ($mgCO_2\ kg^{-1}\cdot d^{-1}$)	qCO_2 (d^{-1})
May-2007	CK	30.5±1.0a	166±3a	1.49±0.03ab
	I	30.2±1.1a	174±7a	1.57±0.07b
	IP	30.0±1.9a	166±7a	1.52±0.07ab
Mar-2008	CK	98.4±8.3b	511±16b	1.42±0.11a
	I	129.1±9.3c	725±15c	1.54±0.09ab
	IP	165.3±9.5d	808±24d	1.33±0.05a

Note: average ±standard deviation (n=3). Different letters in the same row indicate significant difference (p<0.05)

Soil respiration (SR) is an important indicator of soil microbial activity. SR in plots of CK, I-treatment, and IP-treament increased by 208%, 316% and 386%, respectively (Table 4). Significant differences in SR were found between CK and I-treatment, as well as between I-treatment and IP-treatment, indicating that irrigation with TPME and plowing could both elevate SR. Irrigation enhanced SR through the increase of soil microbial population, increasing soil moisture, and stimulating soil microbial activity. Our result was agreed with that of Li et al. (2008), who reported that SR was increased after rainfall. Plowing could improve SR；that is because plowing increases soil population and exposes deeper layer of soil, which accelerates mineralization of organic matter and releases CO_2. Lascala et al. (2006) reported that SR under plowing was as much as several folds of SR under non-plowing condition.

qCO_2 is an indicator that represents the response of soil microbes to environmental stress and interference. The stresses of degraded saline-alkaline soil mainly contain salinity and sodocity, as well as nutrients. The high qCO_2 in the soil before experiment (Table 4) demonstrated that the studied degraded saline-alkaline wetland was high in soil salinity and sodictiy, but poor in soil nutrients. The decrease of qCO_2 in CK plot reconfirmed that anti-waterlogging ditches were competent for leaching soil salts and alkali and for reducing the stress to soil. Overall, at the end of the experiment, qCO_2 was lower in IP-treatment，whereas qCO_2 had no evident change in I-treatment plot, indicating that combination of irrigation with TPME and plowing was effective in reducing soil salinity and sodicity, as well as improving soil nutrients.

Soil enzyme activities

Soil enzymes are capable of accelerating and catalyzing all of the soil biochemical reactions. They play key roles in the materials circulation and energy transformation in soil ecosystem. Enzyme activities are the important symbolization of soil fertility. Figure 3 shows the influences of irrigation with TPME and plowing on soil urease activity, phosphatase activity, and dehydrogenase activity.

Soil urease activities in CK, I-treatment, IP-treatment, IP-treatment plots were significantly improved by 53%, 80%, and 107%, respectively (Fig. 3a), indicating that irrigation with TPME and plowing could significantly improve soil urease activity. Both phosphatase activity (Fig. 3b) and dehydrogenase activity (Fig. 3c) in the CK plot show a decline trend. Compared to CK, phosphatase activity in IP-treatment plot was increased significantly, indicating that the joint action of irrigation with TPME and plowing could significantly improve soil phosphatase activity. Dehydrogenase activities in both I-treatment and IP-treatment were enhanced significantly, indicating that both irrigation with TPME and irrigation with TPME and plowing could significantly improve soil dehydrogenase activity.

Soil enzyme activities are affected by soil water, air, heat, nutrients, salinity, and sodocity, etc. The increase of soil urease activity in CK plot was attributed to a few plants grown in the later period. In winter, plant residue supplied soil urease with

plenty of action substrate. The decrease of soil phophatase activity and dehydrogenase activity in CK plot indicated that phophatase and dehydrogenase were heavily influenced by climate change. Irrigation with TPME and plowing could improve soil conditions of water, air, and heat, alleviate soil salinity and sodicity, increase soil nutrients, improve the environment of microbial growth and proliferation, and stimulate microbial growth to secrete more soil enzymes. Furthermore, irrigation with TPME supplied abundant of metabolizing substrate for enzyme catalyzing, consequently enhanced soil enzyme activities.

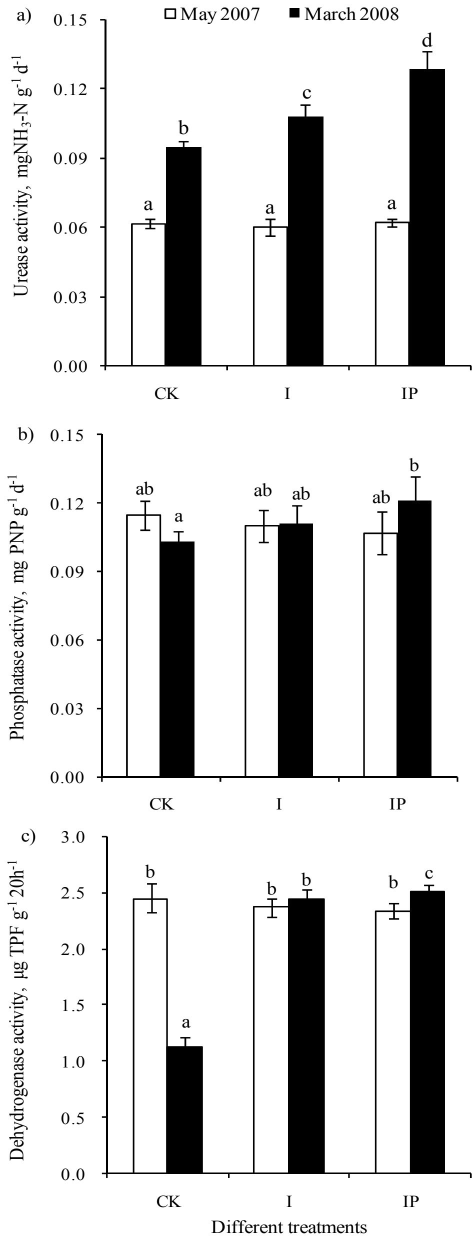

Fig. 3 Influence of irrigation with treated paper mill effluent and plowing on soil urease activity (a), phosphotase (b) and dehydrogenase (c). Different letters represent a significant difference (p<0.05).

Yan and Pan (2010) and Kannan and Oblisami et al. (1990b) reported that irrigation with TPME could increase soil enzyme activities. In contrary to this study, Yang et al. (2008) and Gao et al. (2004) reported that plowing posed adverse effect on soil enzyme activities due to the excessively frequent or over deep plowing. However, soil in the present studied degraded wetland was saline-alkaline; salinity and sodicity were the main stresses compared to the other adverse factors. Thus, the decline of soil salinity and sodicity could significantly improve soil enzyme activities. This is in accordance with the study conducted by Sun et al. (2006).

Correlation analysis between soil salinity, sodicity and other parameters

Soil salinity and sodicity were the two main restrictive factors of remediation of the present degraded wetlands. Correlation analyses between soil TSS and the other parameters, as well as those between SAR and the other parameters were shown in Table 5. The results presented that both TSS and SAR were significantly correlated to soil bulk density, indicating that high salinity and sodicity would make soil compacted and resulted in the increase of soil bulk density. From the correlations between soil TSS and nutrients, as well as between SAR and nutrients, it could be concluded that AN was severely influenced by soil salinity and sodicity as compared to AP. The significant correlations between soil TSS and MBC as well as SR, and these between SAR and MBC as well as SR fully certified that high soil salinity and sodicity inhibited soil microbial population and activity. They also inhibited soil enzyme activity. This could be reflected by the significantly negative correlation between soil urease activity and TSS as well as SAR. However, soil neither phosphatase nor dehydrogenase showed significantly negative correlation with soil salinity and sodicity; demonstrating that compared to urease, phosphatase and dehydrogenase were less influenced by soil salinity and sodicity. Further, compared to SAR, soil TSS was more significantly correlated to other properties, because soil salinity was stronger than sodicity, and the change of soil salts could more significantly impact the other soil properties.

Table 5. Correlation analysis between soil soluble salts, SAR and other properties

	SBD	SOM	AN	AP	AK	MBC
TSS	0.81*	-0.97**	-0.94**	-0.23	-0.98**	-0.99***
SAR	0.88*	-0.76	-0.89*	-0.43	-0.80*	0.91*

	SR	qCO2	Uurease	Phosphatase	Dehydrogenase
TSS	-0.98**	0.71*	-0.99***	-0.28	-0.20
SAR	-0.88*	0.82*	-0.92**	-0.70	-0.16

*represents p<0.05; **represents p<0.01; and ***represents p<0.001.

Conclusions

Paper mill effluent was abundant in plant fiber. Irrigation with paper mill effluent can decrease soil bulk density as it can be held in soil. Plowing also could reduce soil bulk density, because

it could destroy the compacted structure of soil. The results of our study turned out that irrigation with treated paper mill effluent without plowing and with plowing both could reduce soil bulk density.

Soil salinity of the present degraded saline-alkaline wetlands was extremely high, while salinity of treated paper mill effluent used was relatively low; thus, irrigation leached salts out of soil instead of accumulating combined with anti-waterlogging ditches. Plowing before irrigation could stimulate soil salt leaching and make the process of desalination and desodication more efficiently.

Paper mill effluent, which was rich in organic matter, nitrogen and potassium, significantly improved soil nutrients including organic matter, alkali-hydrolyzable nitrogen and available phosphorus by irrigation. Irrigation did not enhance soil available potassium due to the high original potassium content. Plowing resulted in the loss of soil organic matter, but also stimulated mineralization of organic matter and increased soil available nutrients.

Irrigation with treated paper mill effluent introduced new input of microbes; thus it stimulated microbial respiration and enhanced soil enzyme activities. Plowing also increased soil microbial property by improving air circulation. Combined with anti-waterlogging ditches, irrigation with treated paper mill effluent and plowing significantly decreased soil qCO_2, and reaffirmed the decrease of soil salinity and sodicity, as well as the stress to soil microbes by irrigation with treated paper mill effluent.

Plowing might bring the loss of soil nutrients; but as far as the saline-alkaline soil of the present degraded wetlands, the high soil salinity and sodicity are premise and key to the remediation. Thus, it is advisable to implement appropriate plowing in this study.

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